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ABSTRACT. *A model was developed and validated to predict the operational characteristics of heat mat for swine farrowing creep heating. Heat exchange between piglets and heat mat was simulated by a one-dimensional, steady-state heat transfer model. Validation data were collected from three birth-to-wean (14 days) trials under controlled environment of 21°C room temperature and minimal draft (air velocity < 0.15 m/s). The measured maximum contact temperature between piglets and heat mat during the 14-day lactation period ranged from 44.5 to 46.2°C, and was independent of piglet age. The predicted maximum contact temperature was 44.1 and 45.9°C for 1- and 14-day-old piglets, respectively. For typical wintertime production conditions (20°C and minimal draft), the model predicted that a power input of 188 W/m^2 to the mat would be required to maintain thermal neutrality of 1.5 kg piglets. The model further predicted that the power-input requirement would be reduced to 100 W/m^2 for the typical early weaning body weight of 4.0 kg. Environmental conditions (air temperature and velocity) and piglet behavior strongly affect the operational characteristics of the heat mat.*

Keywords. *Piglets, Localized heating, Heat mat, Swine farrowing, Modeling.*

Newborn piglets require relatively high environmental temperature (30~32°C) to prevent excessive body heat loss. However, relatively low room temperature (18~20°C) is more desirable for the comfort of sows and for energy conservation. Thus, it is common to provide localized heat to piglets while keeping a lower room temperature for the sows in swine farrowing barns. Two typical forms of localized heating are radiant heat (most commonly heat lamps) (Xin et al., 1997; Zhou and Xin, 1999) and conductive surface heat (floor heating). Although most swine producers in North America use heat lamps, surface heating is gaining more acceptance.

One of the advantages of surface heating is that it can provide more uniform temperature in the pig rest area than overhead (radiant) heating can (de Baey-Ernsten et al., 1995). Heat mats (pads), which are made of solid or flexible boards with embedded heating elements, have been considered by the swine industry in North America and Europe as an alternative, energy-efficient localized surface heating system. Heat input to heat mats is typically from embedded electrical heating elements or circulating hot water. Electrical heat mats are easy to install in either new barns or existing barns to replace heat lamps. A typical single-size commercial electrical heat mat measures 0.3 m × 1.2 m (1×4 ft) and consumes 60 to 125 W of electricity, which is much lower than heat lamps (175~250 W). The thermal performance of heat mats varies considerably, depending on the mat design and operation (Xin, 1998; Zhang and Xin, 2000). There is little information in the literature on designing and operating heat mats. Xin and Zhang (1999) examined the preference of heat lamp or heat mat by piglets (birth to weaning) under various environmental conditions and revealed that heat mat was generally preferred by larger piglets. Still, there exist a number of practical questions among mat manufacturers and users. For instance, what should be the capacity of the heating elements? What should be the mat temperature setpoints? How should the mat surface temperature be controlled? What is the optimal physical size of the mat? To address these questions, it is necessary to understand the fundamental principles and characteristics of heat mat operation.

The objectives of this study were to elucidate the principles of heat transfer in mat heating and to develop a model for simulating the thermal behavior of heat mats. The model will assist mat designers and users in better understanding heat mat operation.

MODEL DEVELOPMENT

A typical electrical heat mat consists of embedded heating elements, temperature sensors, and a power controller (fig. 1). The mat surface temperature is usually preset to certain levels (commonly 30~40°C) according to the age of piglets, room temperature, and management style. When piglets rest on a mat, the mat is divided into

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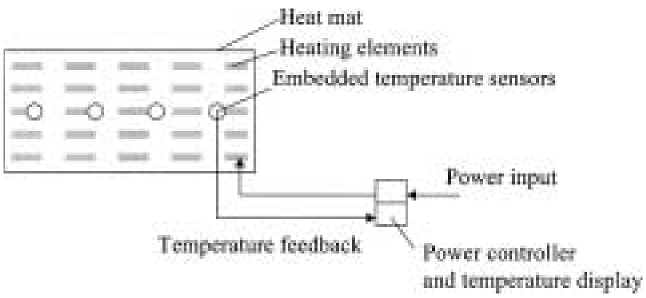

Figure 1–Structure of a typical electrical heat mat.

two regions: a region occupied by piglets and a region not occupied. The mat temperature gradually rises in the occupied region (OR) because the warm body and tissue insulation of the piglets reduce heat loss from the mat surface (Zhang and Xin, 2000). The embedded temperature sensors sense this elevated temperature and send a feedback signal to the controller. The controller then acts on the temperature signal by cutting off or reducing power input to the heating elements. Consequently, the temperature in the unoccupied region (UR) declines (Zhang and Xin, 2000).

Heat transfer between the mat surface and the piglets or between the mat surface and the environment is transient. However, an equilibrium condition is reached if the piglets have been resting on the mat for an extended period. When equilibrium is reached, mat temperature becomes maximum in OR and minimum in UR. This equilibrium condition represents the most extreme variation in the mat temperature.

In this study, a one-dimensional, steady-state heat transfer model is developed to simulate heat transfer between piglets and the heat mat surface under the equilibrium condition. Besides the steady-state assumption, two other assumptions have been made in the model development: (1) heat (electrical energy) input to the mat is uniformly distributed on the mat surface; and (2) heat flows only from the upper (exposed) surface of the mat to piglets in OR or to the environment in UR. The first assumption is reasonable if the heating elements are uniformly embedded in the mat, which is true for most commercial mats (Zhang and Xin, 2000). The second assumption is based on the following three facts: (1) the mat thickness is much less than the other two dimensions; (2) the lower surface of mat is well insulated; and (3) the mat is heated uniformly. With these assumptions, heat flow from the mat may be simplified as a one-dimensional flow (fig. 2). In UR, heat is dissipated from the mat surface to the environment through convection and radiation and the amount of heat loss from the mat surface to the environment equals that supplied by the heating elements, namely:

$$Q_{mu} = Q_{sf} = A_u h_{cr}(t_{mu} - t_a)$$

or

$$q_{mu} = q_m = q_{sf} = h_{cr}(t_{mu} - t_a) \quad (1)$$

where

Q_{mu} = $q_m A_u$, total heat input to UR (W)
Q_{sf} = $q_{sf} A_u$, total heat loss from UR to environment (W)
A_u = area of UR (m^2)
q_{mu} = power (heat) input per unit of UR area (W/m^2)
q_m = power (heat) input per unit mat area (W/m^2)
q_{sf} = sensible heat loss per unit area from mat surface to environment (W/m^2)
h_{cr} = combined convection and radiation surface heat transfer coefficient ($W/m^2 \cdot K$)
t_{mu} = mat surface temperature in UR (°C)
t_a = environmental (air) temperature (°C)

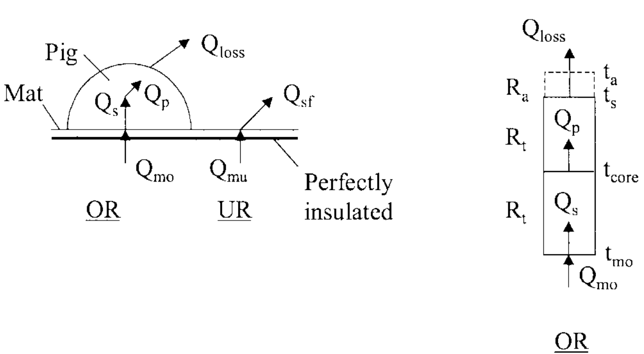

Figure 2–A heat transfer model for piglets on heat mat (OR = occupied region; UR = unoccupied region).

In OR, heat loss from the pig (Q_{loss}) occurs only through the exposed skin to the environment (fig. 2) because the lower surface of the heat mat was assumed to be perfectly insulated. The heat gain by the pig from the mat equals the power input to OR of the mat:

$$Q_{loss} = Q_p + Q_{mo} \quad (2)$$

$$Q_{mo} = Q_s = q_{mo} A_f = A_f (t_{mo} - t_{core})/R_t \quad (3)$$

where

Q_{loss} = total heat from pig to environment (W)
Q_p = heat production by pig at thermoneutrality (W)
Q_{mo} = $q_{mo} A_f$, total heat input to OR of the mat (W)
A_f = contact area between pig and mat (m^2)
Q_s = $q_{so} A_f$, total sensible heat transfer from mat to pig (W)
q_{so} = sensible heat transfer from mat to pig per unit contact area (W/m^2)
R_t = tissue thermal resistance of pig ($m^2 \cdot K/W$)
t_{mo} = mat surface temperature in OR (°C)
t_{core} = core body temperature of the pig, 39.5°C

The contact temperature t_{mo} is one of the most important performance parameters of the heat mat because this temperature is "felt" by the pigs when they rest on the mat. By rearranging equation 3, the contact temperature is predicted as:

$$t_{mo} = t_{core} + q_{mo} R_t \quad (4)$$

Since most farrowing barns are maintained at relatively low temperatures, the maximum tissue resistance, as recommended by Bruce and Clarke (1979), is used in equations 3 and 4.

$$R_t = 0.02M^{0.33} \tag{5}$$

where
M = body mass of individual pigs (kg)

For a newborn piglet at 1.5 kg, equation 5 predicts a tissue resistance value of 0.023 $m^2·K/W$, which is close to the value (0.021) reported by Mount (see Blaxter, 1979) for newborn pigs.

de Baey-Ernsten et al. (1995) suggested a tolerable surface temperature range of 37~43°C for surface heating of piglets. The concern here is how to maintain the contact temperature below the upper limit of the tolerable range t_{tol}. The power input to a mat is then limited by:

$$q_{mo} = (t_{mo} - t_{core})/R_t = (t_{tol} - 39.5)/0.02M^{0.33} \tag{6}$$

The ultimate goal of using heat mats is to maintain thermoneutrality (TN) for the piglets. From the energy balance standpoint, the amount of heat gained by the piglets from the mat should be high enough to compensate the heat loss from the pigs to the environment. Therefore, mat heat (Q_{mo} or q_{mo}) required to maintain TN of the piglets can be predicted from equation 2 when the pig heat production Q_p and heat loss Q_{loss} are known. Heat production by animals is proportional to their metabolic body size (Kleiber, 1961):

$$Q_p = C_h\, M^{0.75} \tag{7}$$

where C_h is a heat production coefficient in $W/kg^{0.75}$, which is dependent on the pig age and feed intake. Holmes and Close (1976) suggested C_h values of 5.72, 6.54, and 7.36 $W/kg^{0.75}$ for young pigs fed on milk at 1×M, 2×M, and 3×M (maintenance), respectively. In the following discussion, the pigs are assumed to be fed 2×M unless noted otherwise.

Heat loss from the pig to the environment consists of a sensible and a latent component, namely:

$$Q_{loss} = Q_a + Q_e \tag{8}$$

where
Q_a = sensible heat loss to environment (W)
Q_e = latent heat loss to environment at the lower limit of TN (W)

The two components are determined as follows (Bruce and Clark, 1979):

$$Q_a = \frac{A_a\left(t_{core} - t_a\right) - Q_e\, R_t}{R_t + R_a} \tag{9}$$

$$Q_e = 0.09(8.0 + 0.07M)M^{0.67} \tag{10}$$

where
A_a = pig surface exposed to environment (m^2)
R_a = thermal resistance of boundary layer of pig surface ($m^2·K/W$)

By substituting equations 7 through 10 into 2, the power density of a mat required to maintain TN of the pigs can be determined as:

$$q_{mo} = \frac{A_a\left(t_{core} - t_a\right) - 0.09\left(8.0 + 0.07M\right)M^{0.67}R_t}{A_f\left(R_t + R_a\right)} + \frac{0.09\left(8.0 + 0.07M\right)M^{0.67} - C_h M^{0.75}}{A_f} \tag{11}$$

To solve equation 11, the boundary layer resistance and the contact areas need to be evaluated. The following empirical equations were used (Bruce and Clark, 1979):

$$R_a = \left(5.3 + 15.7\,\frac{v^{0.6}}{M^{0.13}}\right)^{-1} \tag{12}$$

$$A = 0.09M^{0.6} \tag{13}$$

$$A_f = \lambda A \tag{14}$$

$$A_a = A - A_f - A_c \tag{15}$$

$$A_c = 0.15A[(n-1)/n] \tag{16}$$

where
v = air velocity (m/s)
M = body mass of pig (kg)
A = total surface area of pig (m^2)
A_c = contact area between pigs (m^2)
λ = ratio of floor (mat) contact area to the total surface area
n = number of pigs in the group

Equation 11 may also be used to predict the lower critical temperature (LCT) for the piglets on heat mat when power input to the mat is known. That is:

$$LCT = t_{core} - \frac{\left(q_m A_f + C_h M^{0.75}\right)\left(R_t + R_a\right) - 0.09\left(8.0 + 0.07M\right)M^{0.67}R_t}{A_a} \tag{17}$$

Experiment for Model Validation

An experiment involving three trials was conducted in a two-crate farrowing room to collect data for validating the simulation model. The room was well-insulated, practically draft-free, and maintained at 21°C. Two enlarged farrowing crates (1.94 × 2.13 m) were used in the tests, both with woven-wire flooring for the sow and plastic slats for the piglets (see Zhang and Xin, 2000, for details). One double-size mat was placed in each crate on the right (crate 1) or left (crate 2) side of the sow. The total creep area of each crate was 2.85 m^2, including the mat area of 0.74 m^2 (2 × 4 ft). A sow was brought into each crate about two days before the expected farrowing date for each trial.

The mats, measuring 0.6 × 1.2 m, had uniformly embedded electrical heating elements with a rated capacity of 120 W. When the mats were operated with the temperature feedback control, the power input to the mat changed instantly, depending the mat usage by piglets. The constantly changing power input made it impossible to use the data for model validation because power input to the mat must be known in the model simulations. Therefore, the temperature feedback was disabled and constant power input of 188 W/m^2 was maintained throughout the experiment.

Mat surface temperature was measured with type T (copper-constantan) special-limit-error thermocouples (TCs) at a resolution of 0.1°C (Omega Engineering, Inc., Stamford, Conn.) at selected locations. Six TCs ($T_1 - T_6$) were siliconed onto the surface of each mat in two rows (fig. 3). Row 1 (T_1, T_2, and T_3, equally spaced) was along the centerline across the width of the mat, and Row 2 (T_4, T_5, and T_6, equally spaced) was one-fourth into the length of the mat. This arrangement of TCs was expected to cover the mat surface that was most likely to be used by the piglets. Two layers of adhesive (duct) tape were used to protect the TCs from being damaged by the piglets. Temperature signals from the TCs were recorded with a data acquisition system (Model CR10 and AM416, Campbell Scientific, Inc., Logan, Utah) and a PC. Data were sampled every 3 s and stored as 10-min averages.

Results and Discussion

Model Validation

The model was validated by comparing the simulated contact surface temperatures with the measured values. Parameters listed in table 1 were used in the model simulations. Air velocity (v) at the pig level, measured with a precision hot wire anemometer (model MPM 4100, Solomat Neotronics, Norwalk, Conn.), was lower than 0.05 m/s. Therefore, v = 0.05 m/s was assumed to be the calm condition. The mat contact area depends on the comfort level of the pigs lying on it. Bruce and Clark (1979) used 10% and 20% of the total surface area for cold and warm conditions, respectively, for growing pigs. Heat mats are warmer or more comfortable than the bare floor. It was observed from the recorded video images that piglets were mostly lying on mats in recumbent positions, presumably to warm as much of their body surface as possible. Therefore, a ratio of 20% was assumed in the model simulations.

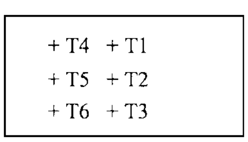

Figure 3–Schematic representation of the thermocouple sensor locations on the heat mat.

Table 1. Parameters used in the model simulations of maximum pig-mat contact temperature

Power input to mat (q_m) (W/m^2)	188
Ambient air temperature (t_a) (°C)	21
Air velocity (v) (m/s)	0.05
Ratio between mat contact area and total pig surface area (λ) (%)	20
Birth weight* (kg)	1.81
Average daily gain* (g)	247
Number of pigs in the group* (n)	12

* Average of three tests.

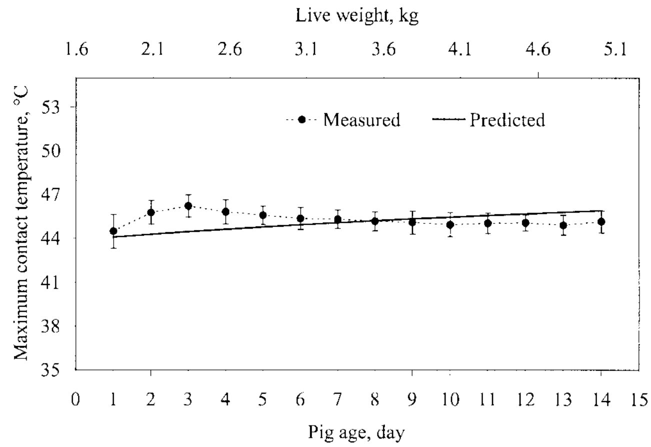

Figure 4–Comparison of maximum contact temperature between model predictions and experimental data (I = standard deviation).

The model predicts that the highest contact temperature occurs only when pigs have been lying on the mat for an extended period of time. In the validation tests, it was impossible to monitor the exact duration of the rest for each piglet in the 14-day test period. Therefore, the measured temperature data were sorted to determine the daily maximum temperatures. This maximum temperature was used to approximate the highest contact temperature. The measured daily maximum temperature ranged between 44.5 and 46.2°C (fig. 4) and the pig age had no significant ($P > 0.05$) effect on the magnitude. It is interesting to note that piglets tolerated a mat temperature as high as 46°C, which is 3°C higher than the upper tolerable limit of 43°C suggested by de Baey-Ernsten et al. (1995). The piglets stayed on the mat even though it was seemingly too warm, presumably because they needed more heat to maintain TN.

The predicted maximum contact temperature increased with pig age, from 44.1°C on day 1 to 45.9°C on day 14. This trend was different from the experimental data and could have been attributed to the assumption of steady-state heat transfer condition between the pigs and the mat. As pigs grow, their tissue resistance increases. Therefore, the pig-mat contact temperature would be higher for larger pigs if they had stayed on the mat long enough (when a steady-state condition was reached). However, pigs would not feel comfortable when the mat surface temperature became too warm, say > 43 to 46°C, and they would move away from the mat before a steady-state condition could be reached. Consequently, the predicted values based on the assumption of steady-state condition were higher than the measured values for larger piglets (older than eight days).

As a whole, the model predictions were in good agreement with the experimental data. The average predicted contact temperature for the 14-day period was 45.1°C, which is almost identical to the overall average measured value (45.3 ± 1.4°C standard deviation).

Simulation Results

Simulations were carried out for typical winter conditions in farrowing barns: room temperature of 20°C and air velocity of 0.15 m/s (“still air”). A litter size of 10 pigs is considered, with a birth weight of 1.5 kg and an

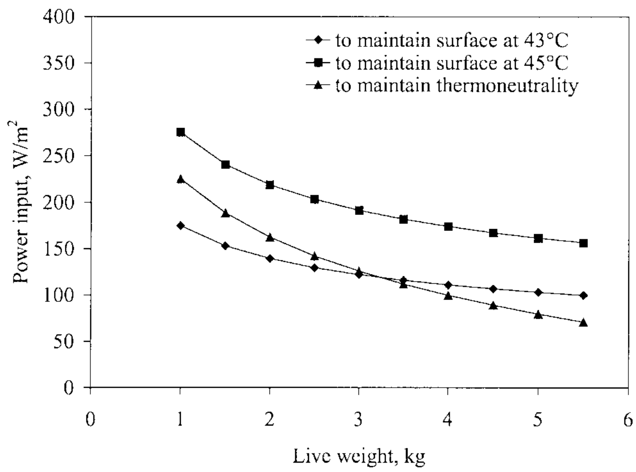

Figure 5–Simulated power requirement for heat mats (t_a = 20°C, v = 0.15 m/s, A_f/A = 20%, fed 2 × maintenance).

early weaning weight of 4.0 kg, and being fed 2×M. The power requirement for maintaining TN of the piglets is predicted to be 188 and 100 W/m^2 for 1.5 and 4.0 kg pigs, respectively (fig. 5). From these simulated values, a typical single-size mat of 0.3 × 1.2 m (1 × 4 ft) would need to have a capacity of 68 W to accommodate newborns (1.5 kg), and the power input can be reduced to 36 W when pigs have reached the weaning weight (4.0 kg). At the full power capacity (188 W/m^2), the mat may become too warm when pigs are on the mat for an extended time because the power required to maintain the contact temperature at a tolerable level of 43°C is lower than that required for maintaining TN for the pigs less than 3.2 kg (fig. 5). If the contact temperature is allowed to rise to 45°C, the predicted power level is higher than that for TN maintenance (fig. 5). In other words, the mat temperature will not exceed 45°C if the mat is powered at the rate for maintaining the TN. We recommend that the design of heat mats follow the power input curve for TN maintenance for the following reasons: (1) piglets may be able to tolerate warmer temperatures (up to 46°C as measured in the experiment) for a short time; and (2) high temperatures occur only when pigs are on the mat for an extended period and pigs can change their postures if the mat becomes too warm.

The mat operation will be affected by the environmental conditions which influence the heat exchange between pigs and environment. Two of the most important environmental variables are ambient temperature and air velocity. The power input required to maintain TN of the pigs increases markedly as ambient temperature decreases (fig. 6) because of the increased heat loss from the pig to the environment. For instance, the power requirement increases from 188 to 325 W/m^2, or a 73% increment for 1.5 kg pigs when ambient temperature decreases from 20 to 15°C. No heat would be needed when ambient temperature reaches 27°C.

When the environment changes from relatively draft-free (0.15 m/s) to drafty (0.30 m/s), the power requirement increases from 188 to 288 W/m^2, or a 53% increment for 1.5 kg piglets (fig. 7). Likewise, power requirement for 0.05 m/s would be 87 W/m^2, or 46% of that for the 0.15 m/s condition. The effect of air velocity on heat mat operation is attributed to the increasing heat loss from the pig to the environment at higher air velocities.

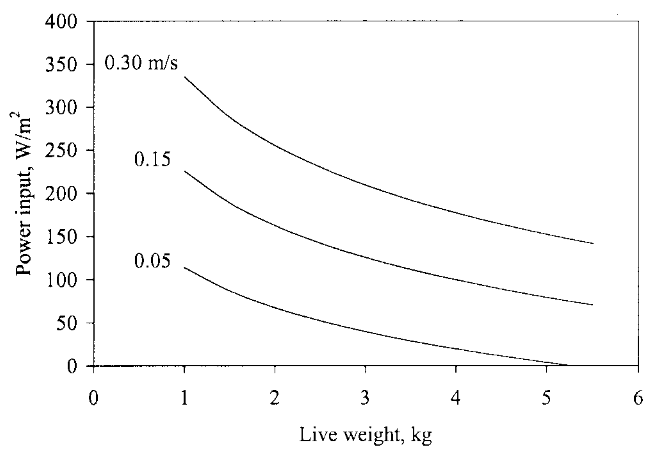

Figure 7–Power input to heat mat required to maintain thermoneutrality of pigs at different draft conditions (air velocities) (t_a = 20°C, A_f/A = 20%, fed 2 × maintenance).

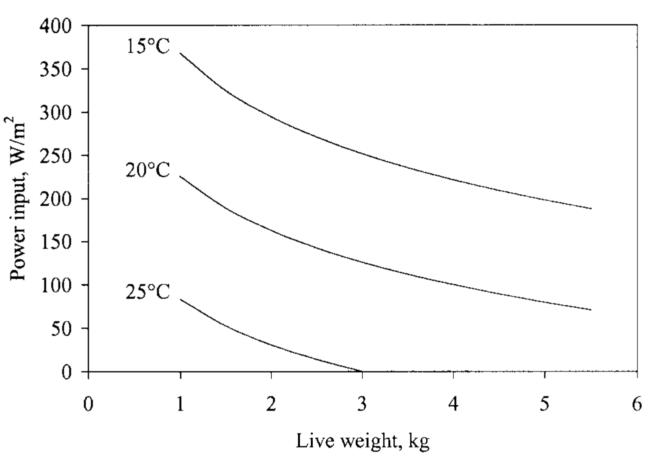

Figure 6–Power input to heat mat required to maintain thermoneutrality of pigs at different environmental temperatures (v = 0.15 m/s, A_f/A = 20%, fed 2 × maintenance).

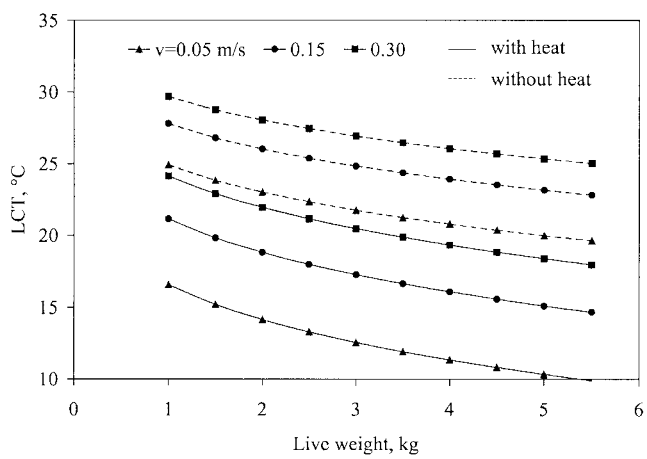

Figure 8–Simulated lower critical temperature (LCT) for pigs on heat mat at different draft conditions (air velocities) (q_m = 188 W/m^2, A_f/A = 20%, fed 2 × maintenance).

Heat input from the mat compensates the pig's heat loss to the environment, thus resulting in lower LCT for piglets on heat mats (fig. 8). When no heat is supplied to the mat (i.e., the mat is equivalent to an insulated solid floor), the LCT for 1.5 kg piglets is 26.8°C under the draft-free condition (v = 0.15 m/s); whereas, the corresponding LCT was 19.8°C when the mat is heated at a rate of 188 W/m^2. The air velocity has more effect on LCT of pigs on the heated mat than on the unheated solid floor (mat). For example, LCT for 1.5 kg pigs increases from 15.2 to 22.9°C, or 7.7°C increase when the air velocity increases from 0.05 to 0.30 m/s for the heated mats; whereas, the corresponding change is from 23.8 to 28.8°C, or 5.0°C increase, for the unheated mat.

Another important variable that influences the thermal comfort of pigs on a heat mat is feed (milk) intake by pigs. Higher milk intake leads to more metabolic heat production and consequently, less mat heating is required. For 1.5 kg pigs, the power input to a mat increases 26% or decreases 25% if the milk intake increases from 2×M (2 × maintenance) to 3×M or decreases from 2×M to 1×M (fig. 9). Similarly, the LCT for 1.5 kg pigs decreases from 19.8 to 18.1°C or increases 19.8 to 21.6°C if the milk intake increases from 2×M to 3×M or decreases from 2×M to 1×M (fig. 10).

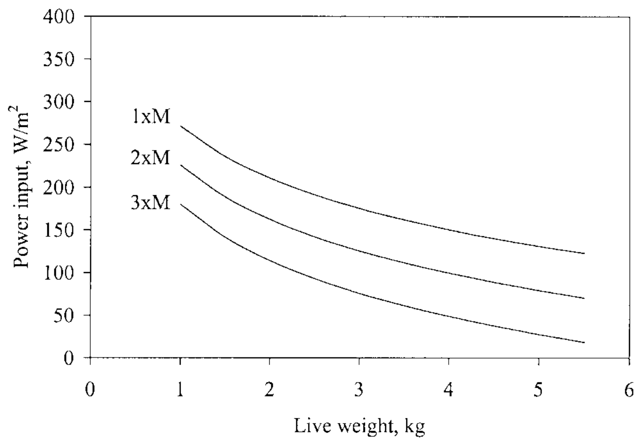

Figure 9–Effect of feed (milk) intake on simulated power requirement for maintaining thermoneutrality of pigs (t_a = 20°C, v = 0.15 m/s, A_f/A = 20%).

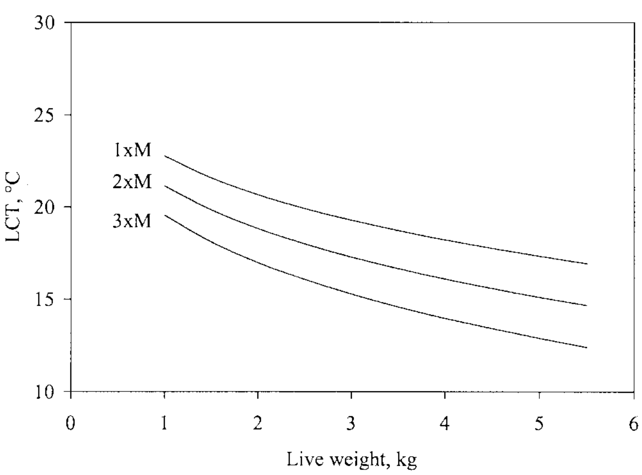

Figure 10–Effect of feed (milk) intake on simulated lower critical temperature (LCT) for pigs on heat mat (q_m = 188 W/m^2, v = 0.15 m/s, A_f/A = 20%).

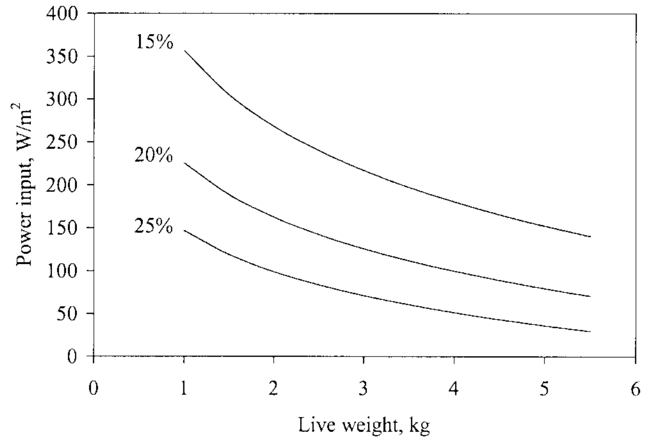

Figure 11–Effect of pig-mat contact area on simulated power requirement for maintaining thermoneutrality of pigs (t_a = 20°C, v = 0.15 m/s, fed 2 × maintenance).

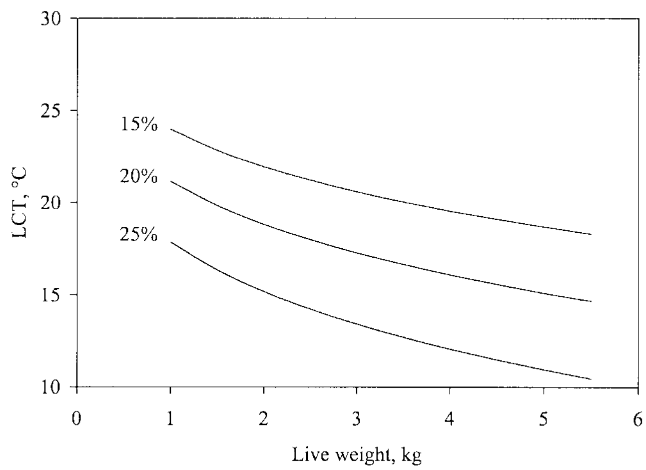

Figure 12–Effect of pig-mat contact area on simulated lower critical temperature (LCT) for pigs on heat mat (q_m = 188 W/m^2, v = 0.15 m/s, fed 2 × maintenance).

In the simulations discussed so far, the ratio of the pig-mat contact area to the total pig surface area has been assumed to be 20%. This ratio has marked effects on the simulation results (figs. 11 and 12). For example, the power requirement increases from 188 to 304 W/m^2, or 1.6 times, for 1.5 kg pigs when the ratio decreases from 20% to 15%. An increase in the ratio from 20% to 25% causes a decrease in the power density requirement from 188 to 119 W/m^2, or 37%. Similarly, the simulated LCT for 1.5 kg pigs changes from 16.3 to 22.8°C when the A_f/A ratio is lowered from 20% to 15%. The results demonstrate/ confirm the efficacy of huddling behavior in conserving body heat loss for pigs exposed to a cold environment. It would be of interest to further determine the pig-mat contact areas for pigs at different ages and for different types of surface heating systems.

CONCLUSIONS

1. The maximum contact temperature between the piglets and the heat mat ranged from 44.5 to 46.2°C, and it was not affected by pig age ($P > 0.05$).
2. The proposed model, based on a theory of one-dimensional, steady-state heat transfer, adequately predicts the maximum pig-mat contact temperature.
3. The simulation results indicate that the heat mat power density required to maintain thermoneutrality (TN) of the piglets might exceed that needed to achieve the maximum tolerable mat surface temperature of 43°C. A design power density capacity of 188 W/m^2, or 68 W for a single-size mat (0.3 × 1.2 m, or 1 × 4 ft), is recommended for maintaining TN of newborns (1.5 kg), and the power density can be reduced to 100 W/m^2, or 36 W per single mat, when piglets have reached an early weaning weight of 4.0 kg.
4. The operational characteristics of heat mats are strongly affected by physical and behavioral factors. The power requirement for maintaining TN of pigs increases markedly with decrease in environmental temperature, increase in air velocity, or decrease in energy intake. The ratio of pig-mat contact area to the total pig surface area also has a marked effect on the simulation results.

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